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The benefit of high-resolution operational weather forecasts for flash flood warning

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Abstract

In Mediterranean Europe, flash flooding is one of the most devastating hazards in terms of human life loss and infrastructures. Over the last two decades, flash floods brought losses of a billion Euros of damage in France alone. One of the problems of flash floods is that warning times are very short, leaving typically only a few hours for civil protection services to act. This study investigates if operationally available shortrange numerical weather forecasts together with a rainfall-runoff model can be used as early indication for the occurrence of flash floods. One of the challenges in flash flood forecasting is that the watersheds are typically small and good observational networks of both rainfall and discharge are rare. Therefore, hydrological models are difficult to calibrate and the simulated river discharges cannot always be compared with ground "truth". The lack of observations in most flash flood prone basins, therefore, lead to develop a method where the excess of the simulated discharge above a critical threshold can provide the forecaster with an indication of potential flood hazard in the area with leadtimes of the order of the weather forecasts.

This study is focused on the Cévennes-Vivarais region in the Southeast of the Massif Central in France, a region known for devastating flash floods. The critical aspects of using numerical weather forecasting for flash flood forecasting are being described together with a threshold – exceedance. As case study the severe flash flood event which took place on 8–9 September 2002 has been chosen. The short-range weather forecasts, from the Lokalmodell of the German national weather service, are driving the LISFLOOD model, a hybrid between conceptual and physically based rainfall-runoff model. Results of the study indicate that high resolution operational weather forecasting combined with a rainfall-runoff model could be useful to determine flash floods more than 24 hours in advance.

1 Introduction

Flash floods are rapidly developing floods with devastating effects for the environment and high risk of loss of life. In Mediterranean Europe, flash flooding is classified as one of the most devastating hazards in terms of human life loss and infrastructures (Gruntfest and Handmer, 1999). Over the last two decades, flash floods produced a billion Euros of damage in France alone (Huet et al., 2003, in French). Beside the economic impact, flash-flood are life threatening: 11 victims were reported in the 1988 Nîmes event, 58 during the Vaison la Romaine flash-flood (1992) (Senesi et al., 1996), 35 for the Aude storms (1999) (Ducrocq et al., 2003) and 24 for the 2002 Gard event (Delrieu et al., 2005; Huet et al., 2003) which is presented here. The vulnerability to flash floods is probably going to increase in the next decades due to evolving land use and the modification of the pluviometric regime associated to the evolution of the climate.

A flash flood is typically the consequence of a short duration storm event The term “flash” refers to the rapid response, with water levels in the drainage network reaching a crest within minutes to a few hours after the onset of the rain event, leaving extremely short time for warning. Flash flood generating storms can accumulate more than 200 mm during less than 6 h over natural watersheds ranging in area from 25 to 2500 km^2 (Creutin and Borga, 2003; Collier, 2007). Over built-up areas of 1 to 100 km^2, flash floods can be produced by storms of even shorter duration with accumulations of over 50mm in less than one hour (Creutin and Borga, 2003; Collier, 2007). The rising rate of waters of several $m.h^{-1}$ and the flow velocity of several $m.s^{-1}$ make these floods far more dangerous for human lives than large river floods (excluding dam breaks). Furthermore, the danger also comes from the rarity of the phenomenon which imposes a new observation strategy as well as new forecasting methodology.

The meteorological conditions leading to flash floods are mostly severe convective systems that typically develop under potentially unstable conditions released by very localized trigger mechanisms. Due to their very localized nature, the observation of these events with gauging network is problematic. Weather radars can provide better spatial rainfall estimations, however, it has been demonstrated that the more intense the rainfall, the less reliable the rainfall estimates from radar become (Austin, 1987). Therefore accurate monitoring and prediction of severe storm rainfall intensities remains yet a major challenge. Prediction of these events with numerical meteorological models is even more difficult (Fritsch et al., 1998; Anquetin et al., 2005; Chancibault et al., 2006; Yates et al., 2007) due to the strong interaction of different physical and micro-physical processes across different scales.

One accepted method for predicting flash floods in ungauged river basins is so called “flash flood guidance” (Georgakakos, 2006). Flash flood guidance is a general term referring to the average rain needed over an area and during a specific time necessary to initiate rapid flooding in small streams. Depending on the method also the antecedent soil moisture or precipitation from previous days is taken into account.

However, there is no unique and simple theory about the runoff production on watersheds during flood events. The main reason is that a variety of processes can be involved which are usually grouped in two categories: saturation excess (Dunne process) or infiltration excess (Horton runoff). Due to the high heterogeneity and space variability of the watershed characteristics (land use, soil type and depth, subsoil, local slope, usptream contributing area) and to antecedent moisture conditioning, these processes are likely to be active at the same time in various combinations.

Therefore, in order to forecast flash-floods reliably, the temporal and spatial resolved scales of the meteorological and hydrological model should be linked. Recognition of the need to couple meteorological and hydrological processes in interpretative studies and in the development of predictive models for flash floods has been demonstrated (Anquetin et al., 2004).

In this study a regional approach for flash flood warning also in ungauged river basins is being proposed. The concept is based on the principle of discharge threshold exceedances as opposed to a rainfall exceedance (Georgakakos, 2006).

In the following the study area is being described as well as the September 2002 case study (Sect. 2). The hydrological model and the threshold concepts are explained in Sect. 3. In Sect. 4 results are illustrated from a) the long-term simulations used for the threshold calculation, b) the forecasting performance for the case study, and c) from a 6 months control forecasting run. Conclusions and way forward are illustrated at the end.

2 The flash flood event 8–9 September 2002

2.1 The Cévennes – Vivarais region in southern France

The Cévennes-Vivarais region (Fig. 1) is situated Southeast of the Massif Central, the V-shaped Hercynian mountain range of the central part of France (85 000 km^2; i.e. one sixth of the country area). The relief is a southeasterly facing slope starting from the Mediterranean shore and the Rhône Valley. The altitude of the mountain range varies from sea level up to 1700 m (Mount Lozère) over roughly 70 km. The area is characterized by relatively small catchments (few hundreds of km^2) with short response time of less than 12 h. The main Cévennes rivers are Virdourle, Ardèche, Cèze, and Gard. They are characterized by a typical Mediterranean hydrological regime with very low level of water in summer and floods occurring mainly during the autumn

For this study four watersheds are analysed, the Ardèche, the Cèze, the Gard and the Vidourle. The outlets at which comparison of observed with simulated data are performed are listed in Table 1. Only those meteorological and hydrological stations with long-term records from 1990 to 2002 were chosen. In total, 11 meteorological stations and 15 discharge stations were selected (Fig. 1). Radar information was used from the 2002.09.08 06:00 onward for a period of 36 h.

2.2 Description of the 8–9 September 2002 case study

The 8–9 September 2002 heavy precipitation event was responsible for one of the most important floods ever recorded in the Cévennes–Vivarais region. It caused 24 casualties and an economic damage estimated at 1.2 billions euros (Huet et al., 2003).

The event started early in the morning of the 8th September 2002 with first convective cells forming over the Mediterranean Sea. The convection progressed northward to form inland a mesoscale convective system over the Gard). The quasi-stationary system stayed over the same region until approximately the next morning, and then evolved eastward together with a surface front. For more detail on the event refer to (Delrieu et al., 2005). For the whole event, the raingauge network locally recorded 24 h cumulated rainfall greater than 600 mm (Fig. 2a), which is confirmed by the radar observation (Fig. 2b).

For the Gard and Vidourle river watersheds, the peak discharges were observed to be two times higher than the ten years return period specific discharge (Delrieu et al., 2005; Chancibault et al., 2006). In Fig. 3, the maximum specific discharge recorded or retrieved from a post-event field experiment (Delrieu et al., 2005) presents the intensity of the hydrological response of the watershed within the region. In Fig. 4, most of the estimated peaks indicate specific discharges of more than 5 $m^3 s^{-1} km^{-2}$, with some of them over 20 $m^3 s^{-1} km^{-2}$. These are the most important values ever reported for watersheds of similar areas in France (Delrieu et al., 2005). The 10 yr return period discharge for such catchments is about 2 $m^3 s^{-1} km^{-2}$ in this region. This figure also points out the characteristic size of the watershed affected by the flood for which detailed rainfall fields have to be correctly forecasted.

A more detailed description of the case study can be found in Delrieu et al. (2005), Chancibault et al. (2006) and Nuissier et al. (2007).

3 Hydrological model, input data and methodologies

3.1 The hydrological LISFLOOD model

The hydrological model used for this study is the LISFLOOD model, a hybrid between conceptual and physical rainfall-runoff model combined with a routing module in the river channel. LISFLOOD has been specifically designed for large river catchments (de Roo et al., 2001) but has also been applied to smaller watersheds (Everhardus et al., 2002). A brief model description is given below, more detail can be found in the LISFLOOD manual (van der Knijff and de Roo, 2006).

In LISFLOOD the simulation of fast subsurface flow through macropores (preferential flow), it is assumed that the fraction of the water on the soil surface contributing to preferential flow is a non-linear function of the relative saturation of the topsoil, and that the importance of preferential flow increases as the topsoil gets wetter. For the remaining water that falls on the soil surface, infiltration and surface runoff are simulated using the Xinanjiang approach (Zhao and Liu, 1995; Todini, 1996). The moisture fluxes out of the top- and subsoil are calculated assuming that the flow is entirely gravity-driven. The groundwater system is described using two parallel interconnected linear reservoirs, similar to the HBV-96 model (Lindström et al., 1997). The upper zone represents a mix of fast groundwater and subsurface flow, including flow through macropores. The lower zone has a much slower response and generates the baseflow. Routing of water through the river channel can be simulated with the kinematic or the dynamic wave descriptions (Chow, 1988). Whenever possible parameters in LISFLOOD are linked to physical properties, e.g. soil or landuse properties. For five parameters, however, default values are proposed but need to be calibrated for better model performance (Feyen, 2005; van der Knijff and de Roo, 2006). Analysis of model parameter uncertainty and its impact on discharges simulated by the LISFLOOD model is presented in Feyen et al. (2007).

For this study the model has been set-up for a region including all basins with a 1 km grid. Time steps are adapted to the resolution of the input variables available for this study. For the long term simulations these are daily and for the detailed case study calculations hourly. Since the aim of the study is to test the approach for ungauged river basins, the available discharge data have been used for comparison and validation only, and not for calibration. Instead, default values for the parameters have been used throughout the study (van der Knijff and de Roo, 2006).

3.2 Input data for the study

For the determination of the hydrological regime over the past years, synoptic meteorological station data from the data archive of the AgriFish[1] unit at the DG Joint Research Centre have been used. Their database holds reliable meteorological data from about 2000 stations across Europe since 1990. In the study area 11 meteorological stations are available for which daily values of temperature and rainfall have been reported and potential evaporation estimated.

For the case study hourly meteorological and hydrological data are available from the databank of the *Observatoire Hydrométéorologique Méditerranéen – Cévennes – Vivarais* (OHM[2]-CV) which has been initiated in 2000 to understand intense Mediterranean storms that lead to devastating flash floods.

Rainfall data estimated from radar was derived from the Bollène 2002 experiment (Chapon, 2006; Boudevillain et al., 2006) designed by DSO/Météo-France and LTHE. This experiment aimed at evaluating the benefit of a radar volume-scanning strategy (8 elevation angles in 5 mn) for radar quantitative precipitation estimation in the Cévennes-Vivarais region. The 3 Plan Position Indicators (PPIs) corresponding to the elevation angles needed for the operational products in real time of the Bollène radar (Météo-France; Fig. 1) were complemented by two sets of 5 PPIs (elevation angle from 0.4° to 18°), alternated every 5 mn. This protocol allowed a good sampling of the atmosphere at a 10mn sampling interval. The data available at 1×1 km^2 resolution was the average reflectivity and the mean absolute reflectivity difference averaged over the individual radar polar bins which centers fall within the corresponding Cartesian mesh. Innovative algorithms were developed in order to identify and correct various errors sources in quantitative precipitation estimation in mountainous regions (i.e. radar calibration, ground clutter identification, vertical profile of reflectivity versus rainfall). Calibration based on rainfall observations has not been used. For more details on each step of the

[1] http://agrifish.jrc.it

[2] http://www.lthe.hmg.inpg.fr/OHM-CV/

radar data treatment see Boudevillain et al. (2006).

High-resolution operational weather forecasting data are provided to the JRC for research by the German national weather service (DWD). In 2002 the Lokalmodell of the DWD had a grid spacing of 7 km, an hourly temporal resolution, and a forecasting lead time of 48 h. The DWD forecasts are provided every 12 h starting at 00:00 UTC and 12:00 UTC.

For the long-term simulations discharge data from 15 stream gauging stations were selected from the *Banque d'Eau*[3], the french National database for discharge. At these stations discharge records are available from 1990 onwards. Only those stations were selected where the influence of hydrological structures such as reservoirs, can be assumed to be little. In addition, for 12 out of these 15 stations, also hourly data are available from the OHM-CV for the 2002 event.

3.3 Methodology of discharge threshold exceedances

In order to issue a flood warning a decision making element needs to be incorporated: is the discharge going to exceed a critical threshold or not? The determination of the critical thresholds is crucial, in particular when dealing with watersheds where only few or no discharge measurements are available. For this study a model consistent approach which has been tested previously for early flood warning in large river basins (Ramos et al., 2007; Thielen et al., 2007) is proposed:

1. A long time series simulation based on observed meteorological data is calculated with LISFLOOD. Obviously, the denser the station network, the better rainfalls and subsequent discharge peaks can be captured.

2. For each grid point, the discharges from the long-term time series are evaluated statistically for threshold values, e.g. for return periods or quantiles. Due to the relatively short time series for which reliable meteorological data are available for

[3] http://www.hydro.eaufrance.fr/

this study (1990 to 2002) – the quantiles approach was used. Discharges are ranked from highest to lowest and certain cut-off values chosen as thresholds. The highest discharge is defined as the *severe* threshold level. The one corresponding to the 99% highest discharge is chosen as the *high* threshold level (comparison with observations has shown that this corresponds frequently with observed 1–2 yr return periods), the 98% as *medium* and 97% as *low*.

3. Comparison with observations is performed through exceedance of critical thresholds, e.g. is $Q_{obs}>Q_{critical\ obs}$ when $Q_{sim}>Q_{critical\ sim}$, for each available station.

The major advantage of this approach is that any systematic over- or under-prediction of the model is compensated for. If the model tends to overestimate discharges in a given river reach, for example because of a non-optimized parameterization or lack of processes such irrigation or reservoir operations, this would be reflected in the thresholds as well as in the forecasts. In this way the relative difference of simulated discharge to simulated thresholds but not the actual values are evaluated. The same procedure was used for the calculation of observed thresholds. For visualization, the critical thresholds are coded by different colors (Table 2).

For those stations where observed discharge data are available, the same method has been applied to calculate the corresponding critical values $Q_{critical\ obs}$.

One of the major drawbacks for this study lies with the different time and space resolutions that are imposed by the availability of the data. While for the determination of the thresholds only daily meteorological and hydrological data are available over a sufficient long time, flash floods themselves develop on shorter time scales. It is therefore likely that the calculated thresholds are low compared to the actual peak discharges occurring during flash floods. In a simililar way, the weather forecasting data do not entirely match neither the resolution of the climatological network nor the high-resolution network. Too low thresholds can lead to a high number of false alarms, that could be reduced if the data used to determine the thresholds were of higher resolution. For the purpose of this study, which focuses on early warning for flashfloods, the low threshold values do not necessarily pose a problem as long as the exceedance of the high and severe thresholds is taken as indication only that flashfloods are likely. Quantification and localization of these warnings would have to be confirmed through real-time rainfall measurements with gauges and radar.

4 Results

4.1 Hydrological regime and calculation of thresholds

The hydrological regime of the river basins in the Cévennes-Vivarais region is proposed in Fig. 4 which illustrates the concentration of peak discharges in autumn and spring. Despite the coarse meteorological station network data used as input, the simulations capture the periods of high flows reasonably well. Although peaks are both over- or underestimated, the scatter plot in Fig. 5 shows clearly that the model rather tends to underestimate the discharges. Particularly severe is the underestimation of simulated discharge in the example of the Ardèche.

As emphasized before, it is not the absolute discharges that are of interest in this study but the exceedances of corresponding thresholds. Comparison of the number of threshold exceedances between simulations and observations yield similar results over the 12 yr period (not shown), indicating that the chosen time interval for the calculation of thresholds is sufficiently long.

The exceedances of threshold levels for both the simulated and observed discharges have then been summarized in contingence tables (defined in Table 3) for each of the four threshold levels. Figure 6 shows for the same stations as in Fig. 5 the first three components of this contingence table. Positive rejections, the vast majority of the cases, are not plotted to avoid distortion of the graphs.

The splitting of the contingence tables shows mixed results. When analyzing the data according to the lowest alert class, there are generally more hits than false alarms or misses. The number of misses and false alarms is about equally high. When looking in more detail at the different threshold classes, the results worsen as the severity class increases. These results have, of course, to be analyzed in view of the quality of the meteorological input data and the events analyzed. Flash floods are events that are very localized and there is a high probability that the synoptic station network misses the event – hence a high number of misses. More surprisingly is perhaps the high number of false alarms. This can be partially explained with the temporal resolution of the input data and the corresponding daily time step which can easily introduce a 1 day time shift which in this rigid analysis based on daily values then counts as a miss or false alarm. If the input data was available at a higher temporal resolution and derived from a higher density network, the results would very likely be better. It can be concluded from the long-term study that with the given input data resolution the simulated discharges tend to be considerably lower than the observed ones. Therefore quantitative analysis of discharges could not be used for flood warning, while the threshold exceedance approach allows better identification of events.

4.2 Forecasting the 8–9 September 2002 event

In LISFLOOD the output of the daily long-term simulations are used as initial conditions for the hourly flood simulations.

Comparison between accumulated rainfalls from radar (Fig. 2b), high resolution rain gauge network (Fig. 2a) and weather forecasts (Fig. 7) show that there are large differences in terms of spatial distribution as well as magnitude.

Taking the high resolution rainfall network data as reference, Fig. 2 shows that the radar produced very similar rainfall in terms of quantity and spatial distribution. There is more information on the spatial variability in the radar data as compared to the interpolated gauge data. In contrast, the daily values of the synoptic gauges do not capture the event in its total spatial distribution. The rainfalls are concentrated in the Southeast of the catchment. Also the rainfall quantity is much too low. As for the weather forecasts, the rainfall patterns are shifted too far North as compared to the observation. This is has been observed also for other meteorological models as documented in Anquetin et al. (2005). Also, the overall volume of precipitation has been underestimated by the weather forecasting model, which again has been observed previously for other weather forecasting models.

Figure 8a shows hourly hydrographs based on the radar estimated rainfall and high density raingauge network. Both simulated discharges are compared against the observed discharge at Générargues in the Gard river. In Fig. 8b, the hourly simulated discharges are based on the 7-km resolution weather forecasts from the German National Weather Service at the same outlet.

This graph clearly illustrates the principle of the threshold exceedance. The simulated discharges – even with high resolution radar and gauge data – are 3 times lower than the observed discharges they are reaching (radar) or exceeding (gauges) the severe threshold indicating serious flooding in the Gard. Although the forecasted rainfalls for the region were shifted too far North compared to the observations and comparatively low rainfalls were forecasted over the Gard basin (Fig. 7), the high threshold is being exceeded with all forecasts from the 07th September 12:00 forecast onwards. Also the timings of the forecasted peaks correspond well with the observed peak on 9th September at 6:00 o'clock ±1–2 h. Thus, although the severity of the event is underestimated, there is an early warning indication that flooding can be expected within 42 h, which may not have been expected from the weather forecasts only. Estimating the runtimes of the meteorological and hydrological models as well as data transfer and preparation time of the data to about 6 h, the leadtime is still of the order of 1 day and more (Fig. 8c). In contrast to the Gard basin, the discharge forecasts for the Ardèche overestimated the severity of the event (not shown). Clearly, the benefit of these forecasts lies with the potential early warning of the flood event. As the events draw nearer, the flood forecasters would increasingly make use of the observational networks to identify the spatial distribution and the magnitude of the flooding.

Figure 9 illustrates the spatial development of forecasted event. Again the exceeded alert thresholds are visualized with the colour coding listed in Table 2. Each panel shows the maximum alert threshold exceeded during the forecasting period in 12 hourly steps. The panel clearly illustrates that the event is first forecasted on the 07 at 12:00 to take place in the upstream areas of all 4 river basins. In the next forecasts the emphasis is mostly in the Gard and Cèze rivers and less in Ardèche and Virdourle. The panel shows how the flooding is forecasted to affect almost the whole basins well exceeded the severe thresholds over large parts of the river basins. Downstream, towards the outlets, mostly only high thresholds are exceeded.

Compared to the images delivered by radar (Fig. 2) one can see that the spatial distribution of the event was well captured by the forecasts but that there was a tendency to shift the precipitations too far north. As a result, for example the Ardèche, was forecasted with more rainfall as compared with observations while the Gard did not receive rainfall as much as observed. This is also reflected in the simulations.

In summary one can state that – in this particular case – system as the one presented could have provided early warning of the event to happen more than 24 h in advance with a good estimation of areas affected, timing and magnitude of the event. It appears that the high thresholds derived from the long-term simulations can be used as indicator for flood events when limited area meteorological model input data are used to drive the simulations.

4.3 Assessments of hits, false alarms and missed events over a 6 months forecasting period

Having demonstrated for the case study that a threshold-exceedance system based on high-resolution operational weather forecasts is capable of detecting flash floods more than 24 h in advance, the case study findings are supported by a six months analysis to assess the rate of alarms and missed events. For computational and data availability constraints this study is limited to running all 12:00 DWD forecasts for a six months period from June to December 2002. For the six months analysis only 9 out of the 15 stream gauging stations were available. For the assessment of the six months analysis a flood event is defined as the exceedance of the high alert threshold – simulated and observed correspondingly – at least once during a 24 h period. If the high threshold has been exceeded during two consecutive days it is still only counted as one event. If the forecasted hydrographs exceed the simulated high threshold during any time of the observed event, it is counted as a hit.

For this period the OHM-CV has classified eleven significant rainfall events (3, 5, 8–9 Sep, 9–10, 21, 30–31 Oct, 14,21 and 24 Nov and 10–11 and 27 Dec), where a significant event is defined when at least one station has reported more than 50 mm of rainfall during the event. Out of these eleven rainfall events six have resulted in a flood event (9 Sep, 10 Oct, 22 and 24-27 Nov, 11–13 and 29 Dec) where a flood event is defined as the observed discharge data having exceeding the observed high threshold.

Table 4 summarises the number of hits, false alarms and misses for the period from 5 June 2002–31 December 2002. Positive rejections are not listed.

Over the six months period there are more false alarms (17) than hits (13) and the number of misses is lowest with nine. From Table 4, it seems striking that missed events occurred mostly in the winter months. A closer look at the December events showed that the weather forecasts were shifted too far North where more precipitation was simulated as snow than was observed. In some cases of false alarms the simulated thresholds were only slightly exceeded with the simulations while they just did not reach the observed thresholds. One of the reasons that the number of false alarms is higher than the hits is because the weather forecasts tend to spread the precipitation over larger areas than actually occur. As a result flooding was simulated in almost all river basins while it only occurred in one or two. The threshold method as presented in this paper does not show whether a threshold is only just exceeded or reached.

In terms of early warning the missed events are the most serious ones because they do not induce any precautionary measures, while early warning of false alarms can easily be identified through weather observations and radar prior to the event.

It can be concluded from the long-term study that a six months period for the statistical assessment of hits and false alarms is not long enough. The analysis indicates, however, that the method captures the major flood events, the forecasted rainfalls are often too wide spread resulting in a high number of false alarms. The number of missed events is comparatively low, which is important since missed events are the most undesired ones in terms of early flood warning.

5 Summary and conclusions

In this paper the possibility of interfacing short-range numerical weather forecasts with a spatially distributed rainfall-runoff model for early flash flood warning in ungauged river basins has been explored. The methodology is based on flood threshold exceedances where the thresholds are derived from long-term simulations with an essentially uncalibrated hydrological model. The same model is then used with weather forecast data and the model consistent thresholds applied for the analysis.

The proposed forecasting strategy addresses a number of shortcomings typically present in flash flood forecasting, namely coarse meteorological station networks and few or no discharge station data.

Results of the study show that by looking at relative differences and model consistent thresholds early warning for flash floods can be given with lead-times exceeding 24 h. In the case of the 8–9 September 2002 event the weather forecasts together with threshold exceedance method allowed to capture the timing and severity of the event with an absolute lead-time of more than 36 h. In terms of spatio-temporal distribution the event was forecasted too far in the North, leaving the Gard river basin only with high and not severe threshold values exceeded. Taking into account computing, processing and analyses time the effective lead-time could still have been of the order of 24 h. A 6-months analysis confirms that the approach is capable of capturing the major events, however, due to the wider spread forecasted rainfalls also the number of false alarms is relatively high. The number of misses, however, is comparatively low. This is important since missed events in terms of early warning are more important than false alarms which can be easily identified in the subsequent hours. In the case of a missed event, however, the benefit of early preparedness measures is lost.

A first attempt of combined analysis of the physical and human responses to this devastating Mediterranean storm (Ruin et al., 2008[4]) shows that most of the casualties were not prepared (i) to the strength of the event and its consequences in terms of water speed and (ii) to the time evolution of the storms. In 2002, the warning system, mainly based on the meteorological forecasts, was not designed to give a hydrological signature of the forecasted event. Today, such information could be effectively transmitted through the Schapi, a newly established flood forecasting centre following the devastating series of flash floods in the last decade. Together with the *Observatoire Hydrométéorologique Méditerranéen Cévennes-Vivarais* (OHM-CV) which has now established a high-density measuring network, the performance of such a forecasting system could be greatly improved with better initial conditions, calibrated hydrological model and more realistic thresholds. The radar network could then be for confirmation of the event and more precise developments. The results show, however, that the principle can also be useful for those areas where no data are available and where the approach could greatly contribute to the preparedness for flash flood events in terms of awareness, identification of regions at risk, potential magnitude and timing of the event.

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References

Anquetin, S., Creutin, J. D., Delrieu, G., Ducrocq, V., Gaume, E., and Ruin, L.:Increasing the forecasting lead-time of Weather driven Flash-floods, Joint Research Center, Institute for

[4]Ruin, I., Creutin, J.-D., Anquetin, S., and Lutoff, C.: Human exposure to flash-floods – relation between flood parameters and human vulnerability during a storm of September 2002 in Southern France, J. Hydrol., submitted, 2008.

Environment and Sustainability, H01/812/02/D9056/AG/ct, 33 pp., 2004.
Anquetin, S., Yates, E., Ducrocq, V., Samouillan, S., Chancibault, K., Gozzini, B., Pasi, F., Pasqui, M., Garcia, M., Martorell, M., Romero, R., Silvio, D., Accadia, C., Casaidi, M., Mariani, S., Ficca, G., Chesa, P.: The 8 and 9 september 2002 flash-flood event in France: an intercomparison of operational and research meteorological models, Nat. Hazard. Earth Sys., 5, 741–754, 2005.
Austin, P.: Relation between measured radar reflectivity and surface rainfall. Mon. Wea. Rev, 115, 1053–1070, 1987.
Boudevillain, B., Delrieu, G., Chapon, B., Kirstetter, P.-E., Nicol, J., and Andrieu, H.: The Bollène-2002 experiment: innovative algorithms and evaluation of processing strategies for radar QPE in the Cévennes – Vivarais region, Proceeding of the 4th European Conference on Radar in Meteorology and Hydrology, Barcelona, 157–160, 2006.
Chancibault, K., Anquetin, S., Ducrocq, V., and Saulnier, G.-M.: Hydrological evaluation of high-resolution precipitation forecast of the Gard flash-flood event (8–9 September 2002), Q. J. Roy. Meteor. Soc, 132, 1091–1117, 2006.
Chapon, B.: Etude des pluies intenses dans la région Cévennes-Vivarais à l'aide du radar météorologique. Régionalisation des traitements radar et analyse granulométrique des pluies au sol, PhD Thesis (in French) University Joseph Fourier, Grenoble, 197 p, 2006.
Chow, V. T., Maidment, D. R., and Mays, L. M.: Applied Hydrology, McGraw-Hill,Singapore, 1988.
Collier, C.: Flash Flood Forecasting : What are the limits of predictability ? Q. J. Roy. Meteor. Soc., 133(622A), 3–23, 2007.
Creutin, J. D. and Borga, M.: Radar Hydrology modifies the monitoring of flash flood hazard, Hydrol. Process., 17(7), 1453–1456, 2003.
Delrieu, G., Ducrocq, V., Gaume, E., Nicol, J., Payrastre, O., Yates, E., Kirstetter, P. E., Andrieu, H., Ayral, P.-A., Bouvier, C., Creutin, J.-D., Livet, M., Anquetin, S., Lang, M., Neppel, L., Obled, C., Parent-du-Châtelet, J., Saulnier, G.-M., Walpersdorf, A., and Wobrockl, W.: The catastrophic flash-flood event of 8–9 September 2002 in the Gard region, France: a first case study for the Cévennes-Vivarais Mediterranean Hydro-meteorological Observatory, J. Hydrometeorology, 6, 34–52, 2005.
De Roo, A., Odijk, M., Schmuck, G., Koster, E., and Lucieer, A.: Assessing the Effects of Land Use Changes on Floods in the Meuse and Oder Catchment, Phy. Chem. Earth (B), 26(7–8), 593–599, 2001.

Ducrocq, V., Aullo, G., and Santurette, P.: Les precipitations intenses des 12 et 13 novembre 1999 sur le sud de la France, La Météorologie, 42, 18–27, 2003.
Everhardus, C., de Roo, A., and de Jong, S.: Validation of the LISFLOOD runoff model for a mountainous catchment. Report of the European Commission, Joint Research Centre, EUR 20514 EN, 2002.
Feyen, L.: Calibration of the LISFLOOD model for Europe: current status and way forward, European Commission EUR22125 EN, 2005.
Feyen, L., Vrugt, J. A., Ó Nualláinc, B., van der Knijff, J., and de Roo, A.: Parameter optimization and uncertainty assessment for large-scale streamflow simulation with the LISFLOOD model, J. Hydrol., (332), Issues 3–4, 276–289, 2007.
Fritsch, J. M., Houze, R. A. J., Adler, R., Bluestein, H., Bosart, L., Brown, J., Carr, F., Davis, C., Johnson, R. H., Junker, N., Kuo, Y. H., Rutledge, S., Smith, J., Toth, Z., Wilson, J. W., Zipser, E., and Zrnic, D.: Quantitative precipitation forecasting: report of the 8th prospectus development team, U.S. Weather Research Program, B. Am. Meteorol. Soc., 79, 285–299, 1998.
Georgakakos, K. P.: Analytical results for operational flash flood guidance. J. Hydrol., 317(1–2), 81–103, doi:10.1016/j.jhydrol.2005.05.009, 2006.
Gruntfest, E. and Handmer, J.: Coping with Flash-Flood, Ed. NATO Science Series, 322 pp., 1999.
Huet, P., Martin, X., Prime, J.-L., Foin, P., Laurain, C., and Cannard, P.: Retour d'expérience des crues de septembre 2002 dans les departments du Gard, de l'Hérault, du Vaucluse, des Bouches-du-Rhône, de l'Ardèche et de la Drôme. Technical report, Ministère de l'Ecologie et du Développement Durable, Republique Française, 133 pp., 2003.
Lindström, G., Johansson, B., Persson, M., Gardelin, M., and Bergström, S.: Development and test of the distributed HBV-96 hydrological model, J. Hydrol., 201, 272–288, 1997.
Nuissier, O., Ducrocq, V., Ricard, D., Thouvenain, T., and Anquetin, S.: A numerical study of three catastrophic precipitating events over western Mediterranean region (Southern France), Part I: Numerical framework and synoptic ingredients, Q. J. Roy. Meteor. Soc. (in press), 2007.
Ramos, M.-H., Bartholmes, J., Thielen-del Pozo, J.: Development of decision support products based on ensemble forecasts in the European flood alert system, Atmos. Sci. Lett., 8, 113–119, 2007.
Sénési, S., Bougeault, P., Chèze, J. L., and Cosentino, P.: The Vaison le Romaine Flask flood:

Meso-Scale Analysis and Predictability Issues, Weater Forecast., 11, 417–442, 1996.
Thielen, J., Bartholmes, J., Ramos, M.-H., and de Roo, A.: The European Flood Alert System, Concept and Development, Part I, Hydrol. Earth Syst. Sci. Discuss., 5, 257–287, 2007, http://www.hydrol-earth-syst-sci-discuss.net/5/257/2007/.
Todini, E.: The ARNO rainfall–runoff model, J. Hydrol., 175, 339–382, 1996.
van der Knijff, J. M. and de Roo, A.: LISFLOOD Distributed Water Balance and Flood Simulation Model. Report of the European Commission, Joint Research Centre, EUR 22166 EN, 2006.
Yates, E., Creutin, J.-D., Anquetin, S., and Rivoirard, J.: A scale dependant quality index of areal rainfall prediction, J. Hydrometeorology, 8(2), 160–170, 2007.
Zhao, R. J. and Liu, X. R.: The Xinanjiang model, in: Computer Models of Watershed Hydrology, edited by: Singh, V. P., Water Resources Publications, 215–232, Colorado, USA, 1995.

Table 1. List of river basins, discharge stations and their upstream areas used for this study.

Watershed Ardeche	Station	Upstream area km^2
	Ard102-Pont de Labeaume-V5004010	264
	ARD105-Vogue-V5014010	636
	Ard501-Gravieres-V5045020	476
Ceze	Ceze102-Besseges-V5424010	230
	Ceze104-Roque_sur_Ceze-V5474010	1060
	Ceze106-Chusclan-V5474020	1180
Gard	GAR103-Corbere-V7135010	263
	GAR104-Generagues-V7124010	251
	GAR203-StHilaireBrethmas-V7155040	328
	GAR301-Boucoiran-V7164010	1087
Virdourle	Vid103-Le Vidourle a Souve-Y3414010	190
	Vid105-Le Vidourle a Salinelles-Y3444010	539

HESSD

5, 345–377, 2008

Table 2. EFAS thresholds, their color codes and associated hazard class.

EFAS threshold	Color	Description
S (Severe)	■	Very high possibility of flooding, potentially severe flooding expected
H (High)	■	High possibility of flooding, bankful conditions or higher expected
M (Medium)	■	Water levels high but no flooding expected
L (Low)	■	Water levels higher than normal but no flooding expected

HESSD

5, 345–377, 2008

Benefit of weather forecasts for flash flood warning

J. Younis et al.

Table 3. Definition of contingence table.

	$Q_{obs} \geq Q_{cobs}$	$Q_{obs} < Q_{cobs}$
$Q_{sim} \geq Q_{csim}$	H (Hit)	F (False)
$Q_{sim} < Q_{csim}$	M (Miss)	PR (Positive Rejection)

HESSD

5, 345–377, 2008

Table 4. Number of Hits, False Alarm and Misses out of 178 days of analysis from 5 June–31 December 2002 of flood forecasting based on the 12:00 DWD weather forecasting data.

	Hits	False Alarm	Misses
June	0	0	0
July	0	0	0
Aug	0	0	0
Sep	4	4	0
Oct	2	6	0
Nov	6	6	3
Dec	1	1	6
Summary	13	17	9

HESSD
5, 345–377, 2008

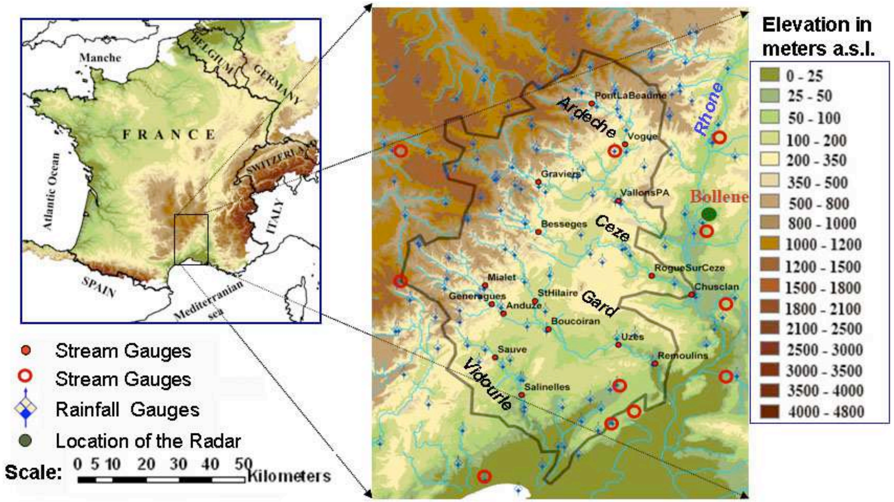

Fig. 1. Map of the topography of France and zoom into the study area of the Cévennes region with the catchments used for this study. Rainfall gauges from high density network (hourly data, blue flags), stream gauging stations (red dots), and synoptic meteorological stations (daily data, red circles). The location of the Bollène radar is also indicated in the map.

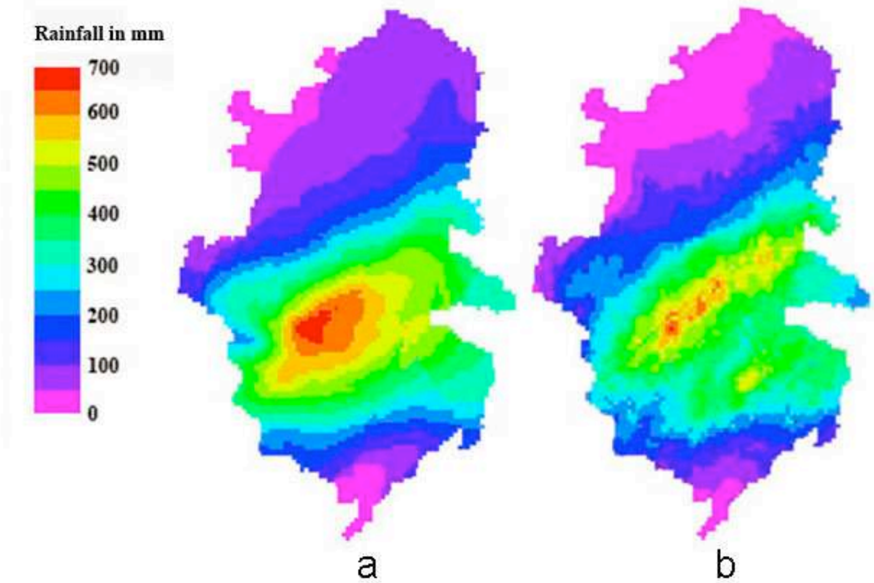

Fig. 2. 48 h accumulated rainfall from 20020908 as **(a)** observed by gauges and **(b)** by radar. The location of the gauges used for the interpolation are as shown in Fig. 1 and the region also as delineated in Fig. 1.

HESSD

5, 345–377, 2008

Benefit of weather forecasts for flash flood warning

J. Younis et al.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀I ▶I
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

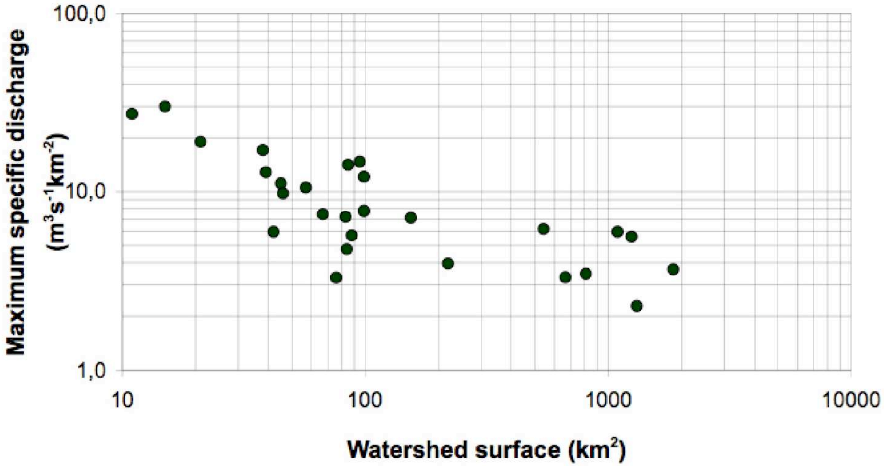

Fig. 3. Observed maximum specific discharges for the flash flood event in September 2002 in the Cévennes-Vivarais region. The plot is based on the data collected in the post-event field experiment as described in Delrieu et al. (2005).

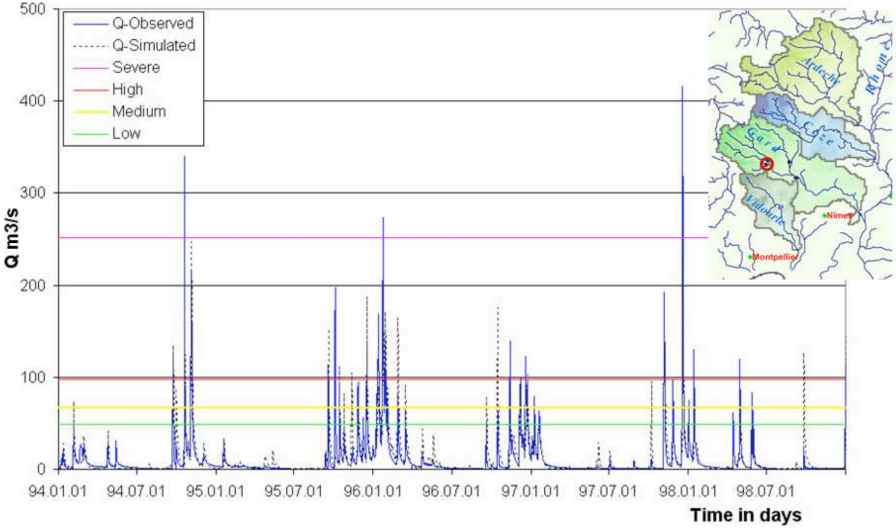

Fig. 4. Observed (Blue) and simulated (Red) Gard discharges at the Corbès (262 km^2) from 1 Jan 1994 to 31 Dec 1998.

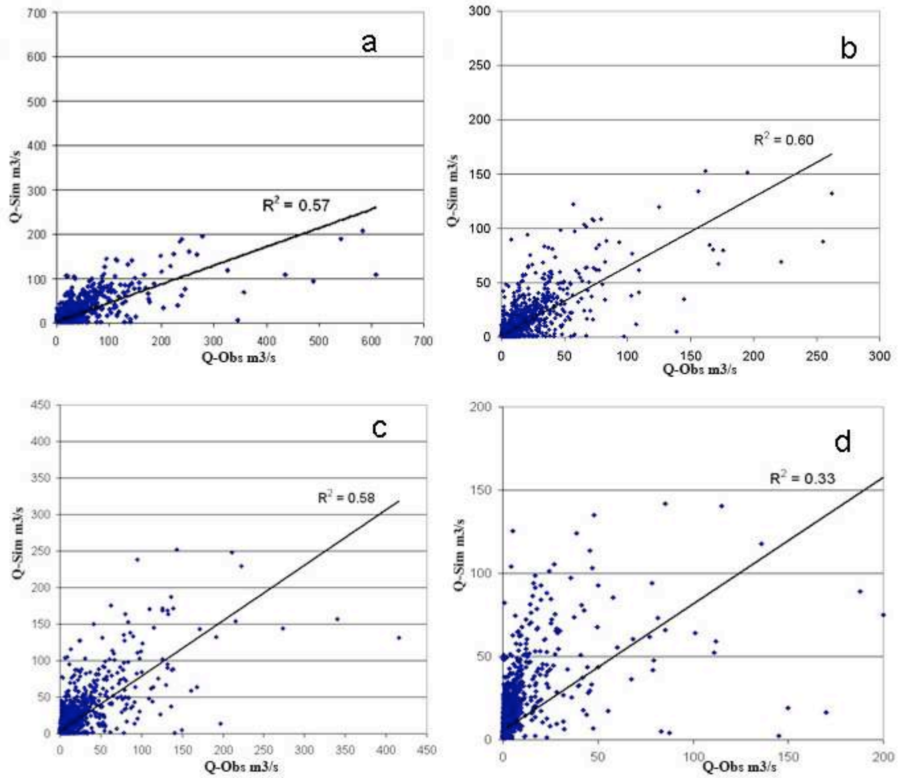

Fig. 5. Scatterplots for the stations in the Ardèche **(a)**, Cèze **(b)**, Gard **(c)** and Virdourle **(d)** with the daily observed discharges in m^3/s on the x-axis and simulated discharges in m^3/s on the y-axis during the 1990 to 2002.

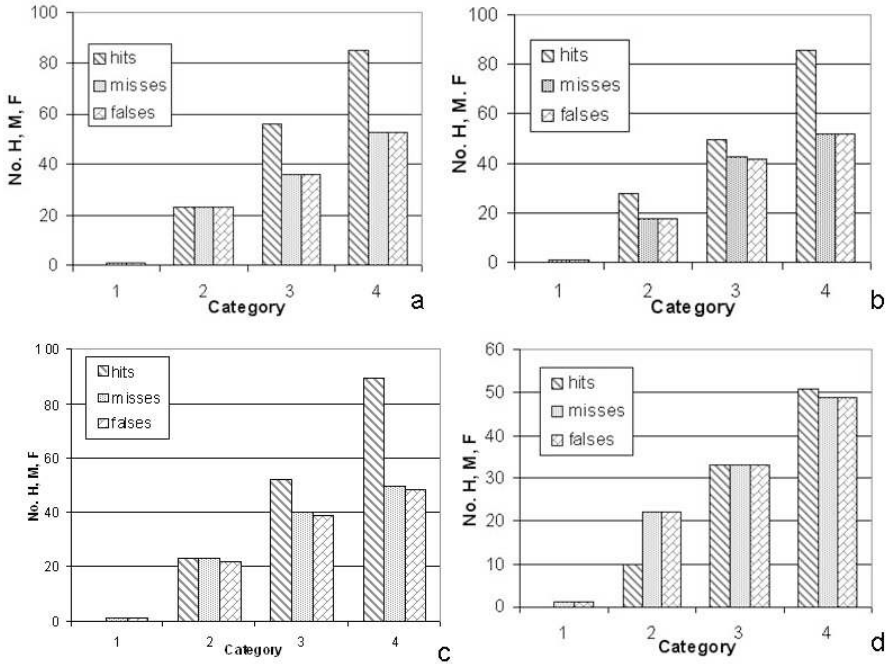

Fig. 6. Contingence tables of hit, false, and missed threshold exceedances for Gravière in the Ardèche **(a)**, Bessège in the Cèze **(b)**, Corbès in the Gard **(c)** and Sauve in the Virdourle **(d)** for the daily discharge exceedance analysis from 1990–2002.

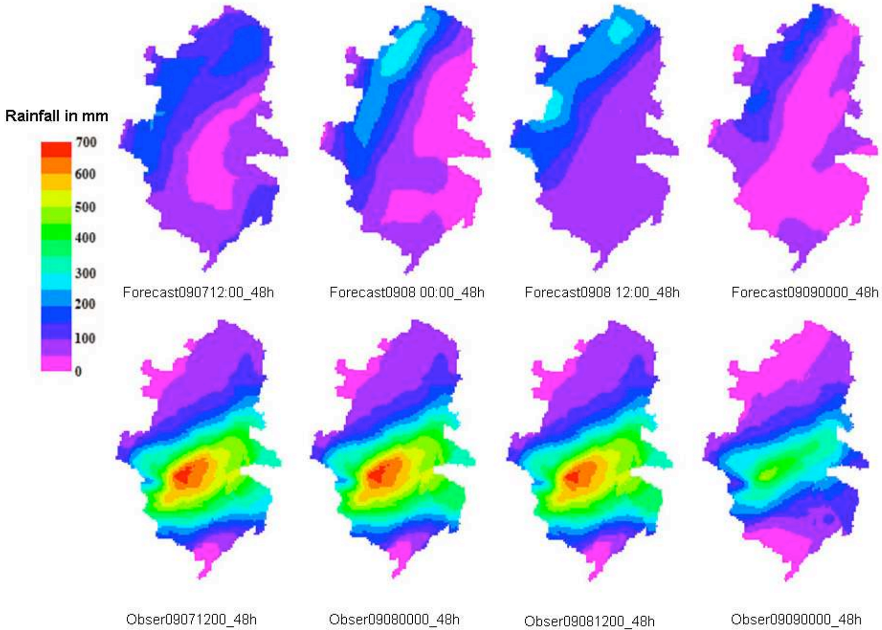

Fig. 7. 48 h accumulated rainfalls from the 20020907 at 12:00, 20020908 at 00:00, 20020908 at 12:00 20020909 and at 00:00, provided by (upper) the DWD forecasts, and (lower) the observations using 101 rainfall gauging stations (see Fig. 1 for the location).

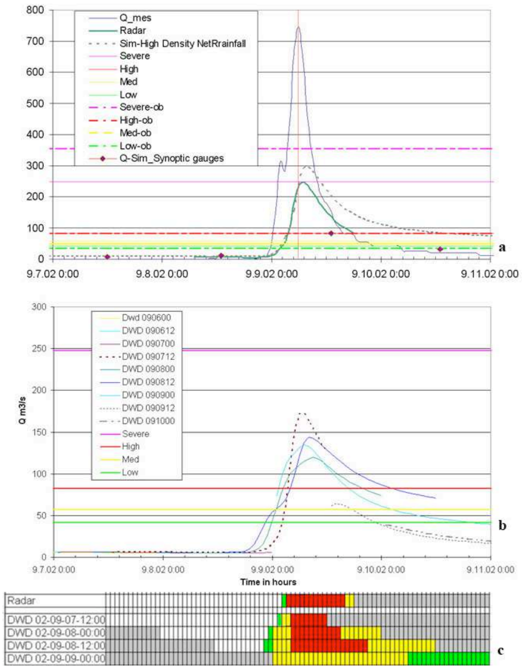

Fig. 8. Observed and simulated discharges in m^3/s (y-axis) for Générargue (244 km^2) in the Gard river. **(a)** Observed hydrograph (blue line), the vertical line indicates the time of peak at 06:00 on 9 September. The simulated discharges obtained by forcing LISFLOOD with the radar observation (green line) and the high density raingauge network (dashed line) present a peak which is slightly delayed of one hour (radar) and two hours (raingauge).**(b)** Hourly forecasted discharges based on DWD forecasts start on 20020906 at 00:00 until 20020909 at 00:00 in 12 h time intervals. **(c)** Visualization of threshold exceedances in hourly time steps for the flood forecasts based on radar data and 48 h DWD forecasts from 20020907 at 00:00, 20020907 at 12:00, 20020908 at 00:00, 20020908 at 12:00 and 20020909 at 00:00. The exceeded thresholds are color coded as purple (severe), red (high), yellow (medium) and green (low). Grey color indicates no data available.

HESSD

5, 345–377, 2008

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◂ | ▸
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

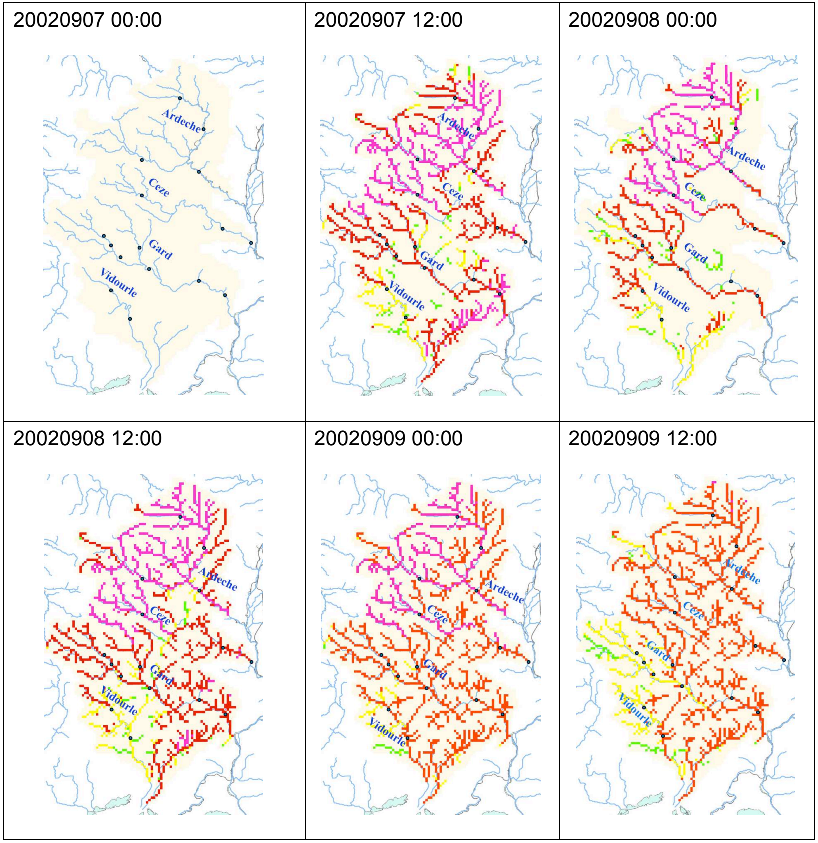

Fig. 9. Summary threshold exceedance maps showing the highest threshold exceeded during the 48 h forecasting time for flood forecasts based on the DWD Lokallmodell weather forecasts from 20020907 at 00:00 and in 12 hourly steps until 20020909 at 12:00. The threshold exceedances are color coded with purple (severe), red (high), yellow (medium) and green (low).